NASA TECHNICAL TRANSLATION NASA TT F 15,206

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(NASA-TT-F-15206) INVESTIGATION OF HEAT TRANSFER FOR TWO VERSIONS OF TURBINE DISK COOLING (Scientific Translation Service) 16 p HC $3.00 CSCL 20M
N74-12573
G3/33 Unclas 23327

Translation of: "Issledovaniye teplootdachi dvukh variantov okhlazhdeniya turbinnykh diskov," Izvestiya vysshikh uchebnykh zavedeniy, seriya "Aviatsionnaya tekhnika," Vol. 8, No. 2, 1965, pp. 56 — 64.

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 DECEMBER 1973

INVESTIGATION OF HEAT TRANSFER FOR TWO VERSIONS OF TURBINE DISK COOLING

V. I. Devyatov

Among the various methods for cooling turbine disks, the radial method (Figure 1a) of cooling is most often used [1 — 5]. Peripheral jet cooling (Figure 1c) is less often used [6, 7]. While for radial cooling there are a number of dimensionless relations for finding both the local and average heat transfer coefficients with consideration of various factors, the situation is otherwise in the case of jet cooling. /56*

At present, only one dimensionless relation [7] for finding the average heat transfer coefficient is known for this method. There are also no data in the literature for the "intermediate" method of cooling (Figure 1b), where the air is supplied by jets at a radius greater than for radial cooling, but less than for peripheral cooling.

An experimental setup, shown schematically in Figure 2, was constructed to find the local heat transfer coefficients over the whole face with disk cooling by a large number of jets and with the air supply: (a) at the periphery of the disk (h/l = 0.875, Figure 1c), (b) by the intermediate method at a distance 1/4 from the start of the channel (h/l = 0.25, Figure 1b). The steel disk 1 (EI-481) of diameter 420 mm and thickness 40 mm was placed in a thermally insulated casing 2. The disk was rotated by an electric motor 3. The cooling air was supplied

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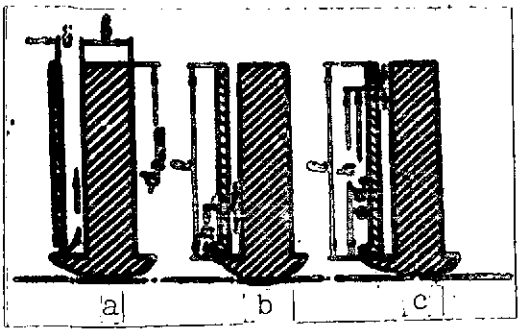

Figure 1. Methods of disk cooling.

a — radial; b — intermediate jet; c — peripheral jet.

to both sides of the disk (symmetrically) through holes 4. The disk was heated over its cylindrical surface by radiation and convection using an electric heater 6. The disk temperatures were measured with chromel-konel thermocouples connected through slip-rings 7 to a potentiometer PP. The thermocouples were made of 0.5 mm diameter wire and were placed on both sides of the disk (20 points), over the heated cylindrical surface (5 points) and over the thickness of the disk at a radius r = 50 mm (e points). With such a distribution of the thermocouples, one could vary the temperature over the cross section of the disk. In addition, the temperatures of the

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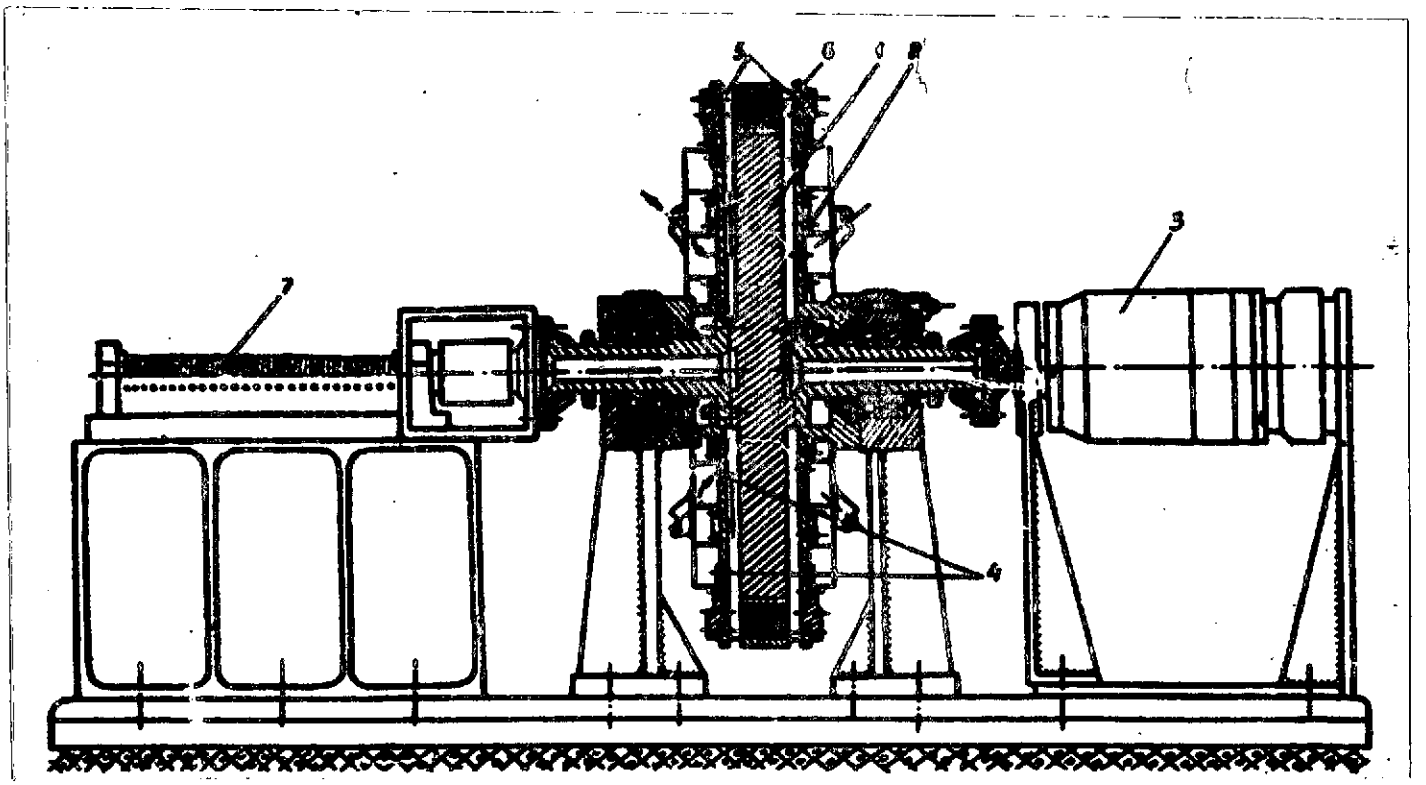
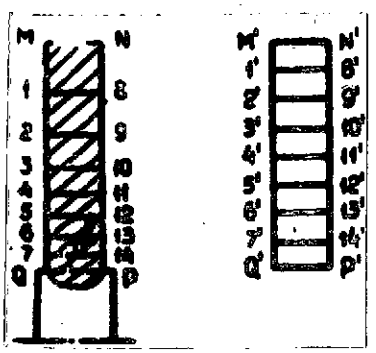


Figure 2. Experimental setup.



a] b]

Figure 3. Partition into sections.

a — disk; b — model.

casing walls and of the air at the input to the air supply holes 4 were measured. After cooling the disk, the air was ejected through holes 5. The magnitude of the local heat transfer coefficients α_l was calculated from the specific heat flux and temperature differences obtained in the experiments under steady-state heat conditions with the formula:

$$\alpha_l = \left[-\frac{\lambda \frac{\partial t}{\partial n}}{(t - t_{cool})} \right] \qquad (1)$$

The temperature gradient $\partial t/\partial n$ in the cross section of the disk (n — normal to its surface) was found according to a method analogous to that used by K. P. Seleznev and A. I. Taranin [8] and also by A. A. Kozdoba [9].

In our case, the temperature gradient was found numerically through the boundary conditions of the first kind with the aid of special tables [10].

The procedure for calculating the gradients over the cross section of the disk was as follows:

1. A cross section of the disk (MNPQ, Figure 3a) is selected from the investigated region.

2. The investigated region is partitioned (in accordance with [8] and [9] into p rings (16 sections) (8 sections are shown arbitrarily in Figure 3b) of equal thermal resistance such that the outer and inner radii of each satisfy the relation:

$$\frac{1}{\lambda_{out}} \ln \frac{r_{out}}{r_n} = \frac{1}{\lambda_n} \ln \frac{r_n}{r_{n-1}} = \ldots = \frac{1}{\lambda_1} \ln \frac{r_1}{r_{in}} \qquad (2)$$

This condition is satisfied if the radii r_i are calculated from the relation resulting from Formula [2]:

$$r_i = r_{in} \cdot e^{k(\lambda_1 + \lambda_2 + \lambda_3 + \ldots + \lambda_i)}, \qquad (3)$$

where r_i is the radius (i = 1, 2, 3, ..., p - 1); i — ring number; p — number of rings; r_{in} — inner radius of the region MNPQ; e — base of the natural logarithms; λ_i — thermal conductivity coefficient of the $i^{\underline{th}}$ section;

$$k = \frac{\ln r_{out} - \ln r_{in}}{\lambda_1 + \lambda_3 + \ldots + \lambda_{out}}$$

r_{out} — outer radius of the disk. The thermal conductivity coefficient (in subsequent calculations) is assumed to be constant for each section, and it is calculated from the temperature found under the condition that the temperature field does not depend on thermal conduction variations. This fact requires the prior partition of the disk into the same p rings by the formula: /59

$$r_i = r_{in} A_1^{i-1},$$

where

$$A_1 = \sqrt[p-1]{\frac{r_{out}}{r_{in}}} \qquad (4)$$

[After calculating the radii r_i from the relations $t^\circ = f(r)$ found in the experiments, the temperatures at these points and the values λ_i are determined, which are then used for the calculations by Formula (2)].

3. A paper model is prepared, more precisely — a drawing of the region of the disk cross section which is partitioned into p identical sections. Correspondence between the points of the disk and the model is established. The points 1, 2, 3, ..., of the disk (Figure 3a) located at the junction of two sections correspond to the points 1', 2', 3', ... of the drawing (Figure 3b).

4. The temperatures for points 1, 2, 3, ... of the disk are recorded on the drawing (model) at points 1', 2', 3', ...,

5. The temperature gradients at points 1', 2', 3', ... are calculated from the boundary conditions of the first kind on the paper model according to the method described in [10].

6. The gradient values found for the model at points 1', 2', 3', ... are transferred to the corresponding points 1, 2, 3, ... of the disk. Then the equation of the curve $(\partial t/\partial n) = f(r)$ is found analytically, from which one can determine $\partial t/\partial n$ at any point over the face of the disk.

7. Calculation of the heat transfer coefficients at the required points is carried out with Formula (1), where the temperature of the cooling air measured at the input to holes 4 (Figure 2) is taken as the defining temperature.

8. Correction for disk radiation is made in the local heat transfer coefficient found from Formula (1).

The amount of heat radiated from the disk is found in the following manner. In view of the small radial temperature gradient of the casing wall compared to the disk, the latter is averaged and calculated from the formula:

$$t_{av} = \frac{\sum t_i f_i}{F}. \quad (5)$$

The disk is partitioned into 16 concentric rings, and the temperature within each is averaged.

The amount of heat radiated from each ring is found in the usual manner:

$$Q_{rad} = \sum_{i=1}^{i=n} 4.9 \cdot \varepsilon \cdot \Delta f \left[\left(\frac{T_d}{100}\right)^4 - \left(\frac{T_c}{100}\right)^4\right] \varphi. \quad (6)$$

Here Q_{rad} is the radiated heat, ε — emissivity; T_d — average temperature of the $i^{\underline{th}}$ ring in °K; T_c — average temperature of the casing in °K; Δf — area of the section element of the ring (Figure 4); z — number of section elements forming the ring; φ — angular coefficient. The angular coefficient is calculated [11] from the formula: /60

$$\varphi = \frac{1}{2}\left[1 - \frac{h^2 + a^2 - R^2}{\sqrt{(h^2 + a^2 + R^2)^2 - 4a^2R^2}}\right]. \quad (7)$$

(The meaning of the arguments of this function is clear from Figure 4.) The experimental procedure was as follows. The disk 1 (Figure 2) is set into motion to the required rpm. Then air is supplied symmetrically to the disk through holes in the casing 4 from both sides at 130 gm/sec, constant temperature

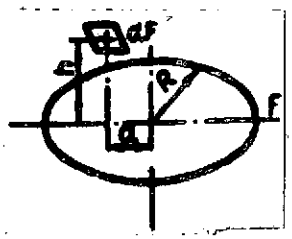


Figure 4. Calculation of the angular coefficient.

(52° C), and pressure p ≅ 1.15 atm. The heaters 6 (Figure 2) are turned on, to which voltage is applied, which is held constant during the experiment.

After the transition to steady-state conditions, the necessary measurements of disk and casing temperatures are made, which are then used to find the analytic dependence of disk temperature on radius and to calculate $\partial t/\partial n$ and the heat transfer coefficients.

Experiments with Cooling by Method No. 1

"Intermediate" jet cooling from both sides (h/ℓ = 0.25, Figure 1b)

Cooling air was supplied at the radius r = 90 mm through 30 holes of diameter 4.3 mm from each side (one-sided cooling is shown in Figure 1b) at 65 gm/sec per side. The Reynolds number Re_j of the jet cooling the disk was $2.8 \cdot 10^4$.

The variation of the temperature fields of the disk and the local heat transfer coefficients was investigated in the experiments with varying peripheral Reynolds number Re_{per} (by varying the disk rpm) and constant Re_j (constant air flow rate). The disk rotation was varied from 1500 to 4000 rpm at 500 rpm intervals, which corresponds to a variation of Re_{per}, calculated at the outer radius of the disk, of $3.68 — 9.8 \cdot 10^5$.

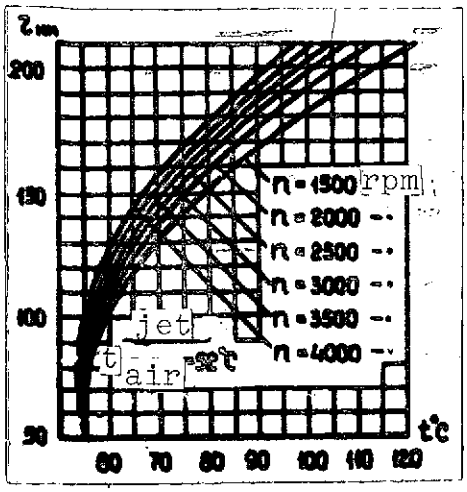


Figure 5. Intermediate jet cooling. Temperature variation with disk radius and rotation.

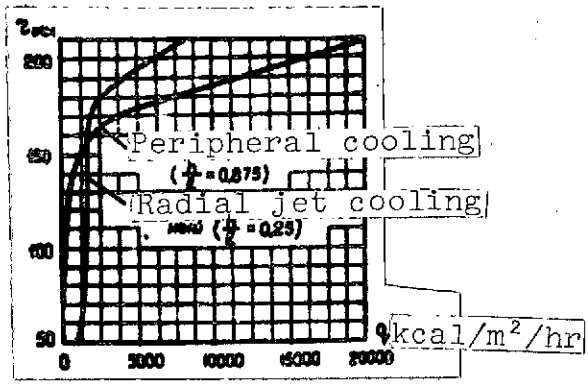


Figure 6. Variation of specific heat flux with disk radius.

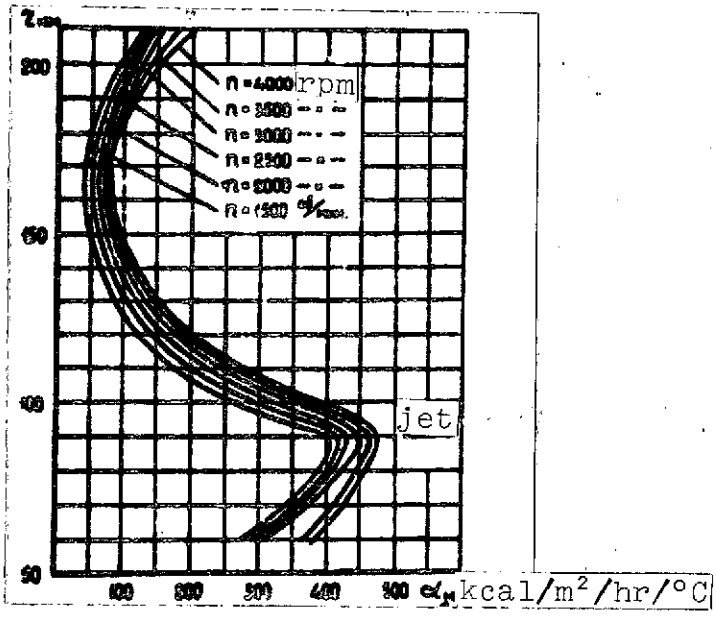


Figure 7. Intermediate jet cooling. Variation of local heat transfer coefficients with rotation.

The temperature gradients in the cross section of the disk were calculated from the temperature distribution over the face of the disk (Figure 5) found in the experiments. The variation of the specific heat flux with disk radius characteristic for this method of cooling is given in Figure 6, and the variation of the local heat transfer coefficients — in Figure 7, where a "peak" in the values of α_{lc} in the region where the jets impact against the disk surface attracts attention. The formation of the "peak" is caused, evidently, by blowing off the boundary layer from the rotating disk in the region of jet impact and also by its high turbulence.

The empirical dimensionless relation was obtained from the test data:

$$Nu_j = 0.046 \cdot K_v^{-0.1} \bar{r}^{2.8} \cdot Re_{per \cdot l}^{0.8} + 0.05 \cdot K_v^{0.18} \cdot e^{-44.1(\bar{r}-0.428)^2} Re_j^{0.8} \quad (8)$$ /61

Here: $Nu_l = (\alpha_{lc} r/\lambda)$ is the local value of the Nusselt number at radius r; α_{lc} — local convection heat transfer coefficient at radius r; $Re_{per \cdot l} = \frac{\omega \cdot r^2}{\nu}$ — local value of the Reynolds number calculated from the peripheral velocity of the disk at radius r; $K_v = \frac{u}{v_r}$ — parameter characterizing the ratio of the peripheral u and the average flow v velocities at the radius of the cooling air inlet; $Re_j = \frac{c \cdot d}{\nu}$ — value of the Reynolds number calculated from the discharge velocity of the jet cooling the disk; c — air discharge velocity from the holes in the casing; d — nozzle diameter; $\bar{r} = r/r_{out}$; r — radius; r_{out} — outer radius of the disk. Formula (8) describes the experimental results with an accuracy of 5% in the investigated range of defining conditions. /62

Experiments with Cooling by Version No. 2

Peripheral jet cooling from two sides (h/l = 0.875, Figure 1c)

Cooling air was supplied at the radius r = 190 mm through 58 holes of diameter 3.1 mm from each side (one-sided cooling is shown in Figure 1c), which corresponds to Re_j of the cooling jets equal to $2.04 \cdot 10^4$. The air flow remained as before, and the rotation was varied the same as for cooling by the previous method. Since it was found from preliminary experiments that peripheral jet cooling is more effective than intermediate jet

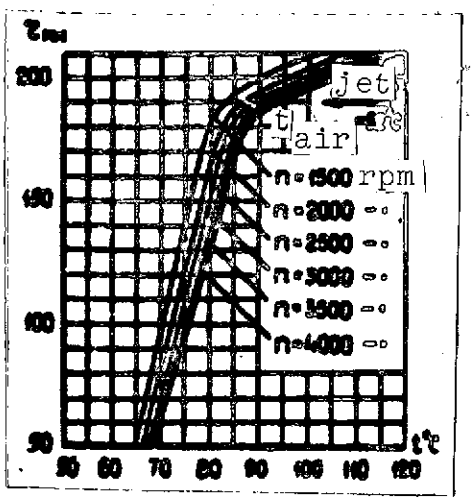


Figure 8. Peripheral jet cooling. Temperature variation with disk radius and rotation.

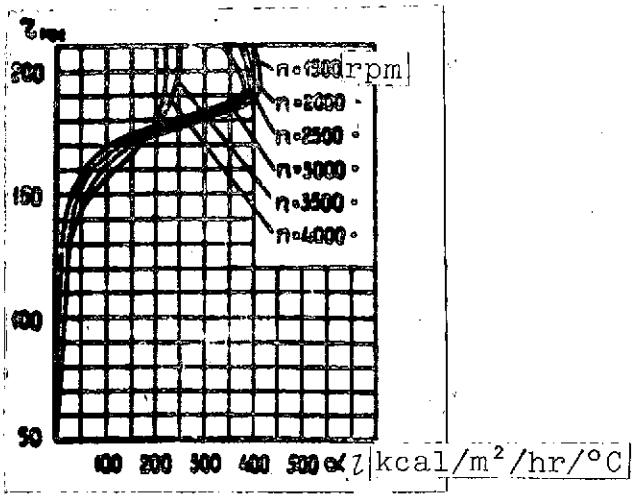


Figure 9. Peripheral jet cooling. Variation of local heat transfer coefficient with rotation.

cooking (over a large part of the investigated range of rotations), the heater voltage was increased to 160 V (as opposed to 127 V in the first case) to produce "steeper" curves for the temperature variation with disk radius. /63

Heating up (Figure 8) of the disk with increasing rpm instead of cooling was observed in the experiments with peripheral jet cooling. Heating up of the disk could be caused either by worsening heat transfer of the disk or by an increase of heat supplied to it due to decreasing heat losses by the heaters 6 (Figure 2) into the cooling fluid. However, after calculating the temperature gradients $\partial t/\partial n$ and subsequent calculation of the local heat transfer coefficients α_{lc} (Figure 9), it was found that heating up of the disk with increasing rpm is caused only by a decrease of α_{lc}. Evidently, the explanation of this phenomenon is to be found in the increasing centrifugal forces: in the repulsion of the cooling jets from the disk

surface with increasing rpm. The maximum α_{lc} in the region of jet impact is clearly seen in Figure 9, and also the peculiar "spreading" of this zone over the disk surface with increasing rpm with a simultaneous decrease in the maximum value of α_{lc}. The decrease of α_{lc} with increasing rpm indicates a significant difference in the heat transfer mechanism between the peripheral and intermediate cooling methods. The variation of specific heat flux with disk radius characteristic for this method is shown in Figure 6.

The empirical dimensionless relation for the latter cooling method has the form:

$$Nu_l = (0.01 + 1.44 \cdot 10^{-4} \cdot K_\nu^{-1.4} \bar{r}^{3} e^{-60(\bar{r}-0.905)^2} Re_j) Re_{per}^{0.8} \qquad (9)$$

Formula (9) describes the experimental results with an accuracy of 10%. The notation is the same as that in Formula (8).

The variation of the average Nusselt number Nu_{av} (calculated from Nu_l) in the form of a function of Re_{per} is given in Figure 10. However, this figure is not characteristic of the dependence of Nu_{av} on Re_{per} only (for curves 1 and 2), since the parameter K_ν varies with variations in rpm. It should be considered as an illustration of the variation of Nu_{av} for constant air flow rate and variable rpm. The solid lines in the figure represent the variation of Nu_{av} calculated from the defining average temperature of the cooling flow, the dashed lines — from the defining initial flow temperature. The variation of Nu_{av} for the freely rotating disk is also shown.

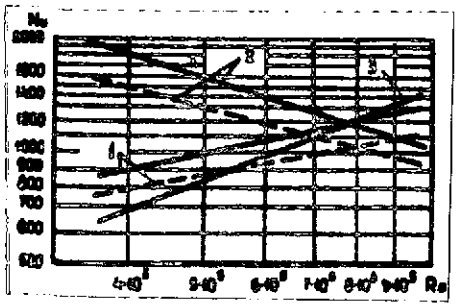


Figure 10. Variation of Nu_{av} with rotation for constant air flow rate.

1 — intermediate jet cooling; 2 — peripheral jet cooling; 3 — freely rotating disk.

Conclusions

In the investigated range of Re_{per}, we found:

1. There is a region of elevated values of the heat transfer coefficients in the region of cooling jet impact against the disk face.

2. For small Re_{per}, increasing the radius of the cooling air inlet leads to a sharp increase of the cooling effectiveness. /64

3. With increasing Re_{per}, the effectiveness of peripheral jet cooling decreases and its advantage over other cooling methods disappears.

Formulas (8) and (9) are suitable for geometrically similar systems of air cooling with the following values of conditions (Figures 1a and 1c).

Cooling method	$\frac{h}{l}$	$\frac{b}{d_{disk}}$	$\frac{\delta}{d_{disk}}$	$\frac{d_0}{d_{disk}}$	$\frac{d}{d_{disk}}$	No. of holes	K_v	Re_{per}	Re_j	λ_{metal}
Intermediate jet	0,25	0,0952	0,0285	0,428	0,0102	30	1,76—4,7	3,68—9,8·10⁵	2,83—104	13,6+0,011t°C
Peripheral jet	0,875	0,0952	0,0285	0,905	0,0074	58	7,88—21,02	3,68—9,8·10⁵	2,04·104	13,6+0,011t°C

*Commas in the numbers indicate decimal points.

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Translated for National Aeronautics and Space Adminstration under contract No. NASw 2483, by SCITRAN, P. O. Box 5456, Santa Barbara, California 93108.